PROCEEDINGS OF SCIENCE

Cross-sections and neutrino oscillations in NOvA

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Uncertainties in neutrino interaction cross-sections affect modern long-baseline neutrino oscillation experiments like NOvA. Detailed within is how NOvA handles these uncertainties, especially for 2p2h interactions, how the effects of these cross-section uncertainties are quantified, and how NOvA's cross-section simulation is tuned to better match data.

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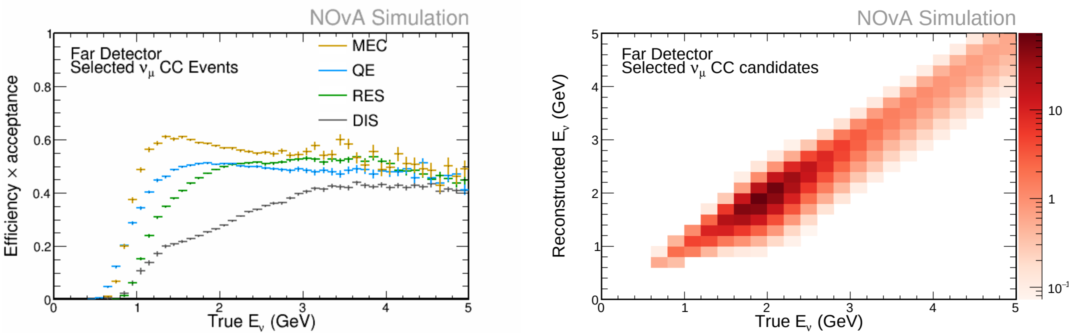
1. Introduction

NOvA is a long-baseline neutrino oscillation experiment that utilizes the NuMI beam from Fermilab. NOvA has a 14-kton finely segmented liquid scintillator far detector (FD) located 810 km from the interaction target and 14.6 mrad off-axis, and a functionally identical 0.3-kton near detector (ND) located 1 km downstream, also off-axis.

NOvA measures neutrino oscillation parameters through two primary channels: the ν_μ disappearance channel, which directly measures θ_{23} and Δm^2_{32}, and the ν_e appearance channel, which directly measures θ_{13} and allows constraints of δ_{CP} and potentially the mass hierarchy. NOvA has released two measurements in each channel, including a joint analysis, and a third is scheduled to be released at the start of 2018. More details about the NOvA experiment and these past measurements can be found in their respective published papers [1] [2] [3] [4].

NOvA relies on measurements of neutrinos in the 0.5-3 GeV range, where many different interaction channels are significant. These are traditionally characterized into a few interaction channels, most notably: quasi-elastic (QE) interactions, where a neutrino interacts on a neutron, resulting in just a proton and a negatively charged lepton; resonance (RES) interactions, where a resonance particle (usually a delta) is created, then decays; and deep inelastic scattering (DIS) interactions, where the neutrino interacts directly on the quarks.

Lately, there has also been evidence in many experiments (including NOvA) for a theorized 2-particle-2-hole (2p2h) mode as well, where the neutrino interacts with a bound pair of nucleons (also sometimes called meson exchange currents, or MEC). It is believed that not including this channel in our simulation was a main reason why there was a significant hadronic energy discrepancy in NOvA's first disappearance analysis.



(a) Efficiency x acceptance for each interaction mode (b) True vs reconstructed energy matrix

Figure 1: Detector effects

Since each of these interaction channels have different final state topologies, they each have different efficiencies in our detectors (Fig. 1(a)), and each have a different amount of energy that goes into neutral particles that may be invisible to our detectors, and thus each have a different reconstructed energy bias. Neutrino detectors measure a reconstructed energy, but oscillations occur as a function of true energy, and we use simulation to map between the two (Fig. 1(b)). Thus, mis-modeling our interaction cross-sections runs the risk of distorting this mapping, which can introduce error into an analysis. This is particularly important for 2p2h events, for which there is no established, tested interaction model yet available.

NOvA has a very rich and high-statistics data set in our near detector that helps provide some guidance. We have taken the approach of taking as much input as we can from other collaborations and the cross-section modeling community, then looking to our own data to fill in the gaps. We use our ND data in two ways: first, as a check that our models aren't terribly wrong, and as a guide when tuning them, and second by extrapolating our ND data when constructing our FD prediction in simulation.

2. Extrapolation

Inevitably, the simulation will not be perfect, but because our near and far detectors are functionally identical in all but size, we expect that most errors will be the same in both. Thus we can use disagreements between simulation and data in our near detector to help correct our simulation in the far detector. The process is as follows: the near detector simulation is compared to data in bins of reconstructed neutrino energy. Bin-by-bin it is scaled to match the data. The simulation contains a mapping from reconstructed to true energy, and this scaled distribution is mapped to true energy. Then the prediction is oscillated and known differences in the near and far detector are accounted for (such as differences in efficiency, taken from simulation). Then we take this predicted far detector true energy spectrum and map it to a far detector reconstructed energy spectrum (using simulation) that we can finally compare to the far detector data to perform our analysis. In this way any differences seen in the near detector are propogated all the way to the far detector as a correction. As this extrapolation procedure starts as scaling factors, it is very good at correcting for overall scale shifts, such as a flux uncertainty, where your overall number of neutrinos may be too high or too low. It does poorly at dealing with energy scale shifts, however. An illustrated example from our first disappearance analysis is shown in Fig. 2.

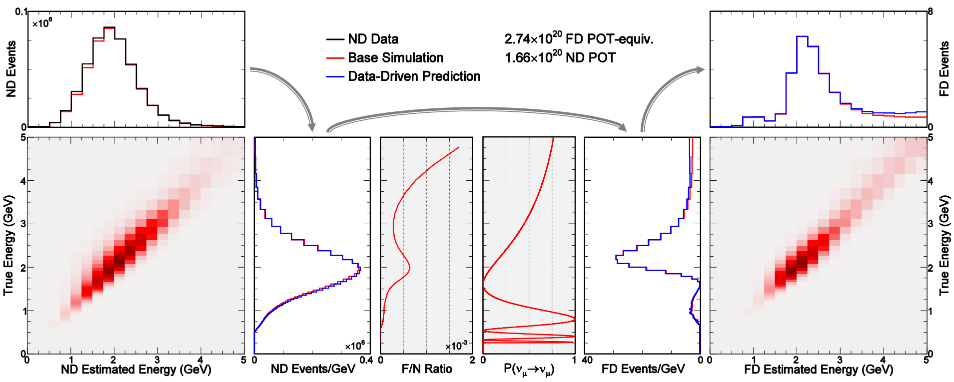


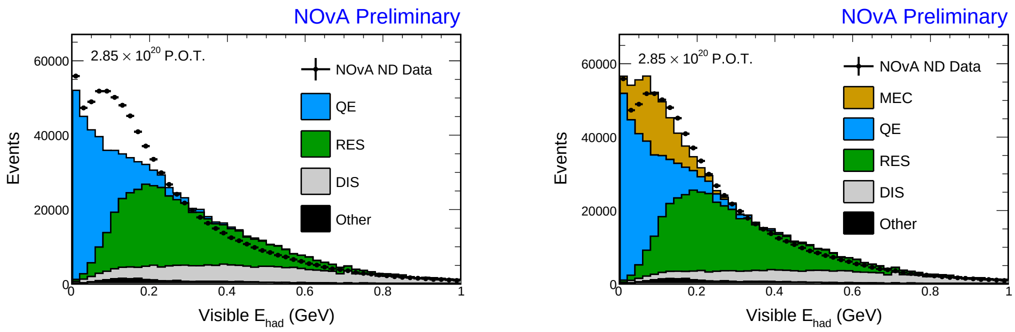
Figure 2: Example from NOvA's first disappearance analysis detailing the extrapolation procedure

3. Cross-section tuning: History

NOvA uses GENIE as our neutrino interaction generator. In our first analyses, we did not include 2p2h and did no cross-section tuning, instead just relying on GENIE output. We had a significant hadronic energy discrepancy in this analysis due largely to the missing 2p2h.

In our second analyses, we included a basic 2p2h model. There is no established model that is known to be right; we used the so called ‘Dytman empirical MEC’ model, mostly due to it being ready for use with GENIE at the time. In these analyses we performed a 2p2h tune to our ND data, as the empirical MEC model has known flaws. A common parameterization of neutrino interaction kinematics is in terms of momentum and energy transfer; for our second analysis tune we set the 2p2h energy transfer distribution to match that of QE events in our simulation and fit the 2p2h momentum transfer distribution to our ND data by slicing in bins of momentum transfer and, for each bin, fitting a scale factor to the 2p2h energy transfer distribution. The resulting set of bin-by-bin scale factors in momentum transfer were then well described by a Gaussian fit. It should also be noted that this first version of the empirical MEC model had a bug that flipped the expected likelihood of the 2p2h bound state being nn vs pn, and we implemented a fix.

In our second analysis we also changed our DIS model to take into account recent bubble chamber data re-analysis [5], which suggested scaling down non-resonant single-pion events. This fix has been part of our simulation tune ever since. This, along with the 2p2h addition and tune, were taken as corrections to the GENIE output. The major place this changed the analyses was in the hadronic energy sector. As a reminder, in the NOvA disappearance analysis most of the neutrino energy, about 75%, comes from the muon, which is taken just from the muon range. As the smaller fraction comes from the hadronic energy estimation, the neutrino energy estimate was never very biased, but the hadronic energy distribution was much improved by the addition of 2p2h and the tune. The difference between using the 2p2h+tuned version and not is shown in Fig 3 for our visible hadronic energy (not full reconstructed hadronic energy).



(a) Without 2p2h or tuning

(b) With 2p2h and tuning

Figure 3: Second analysis tune: ND disappearance second analysis sample

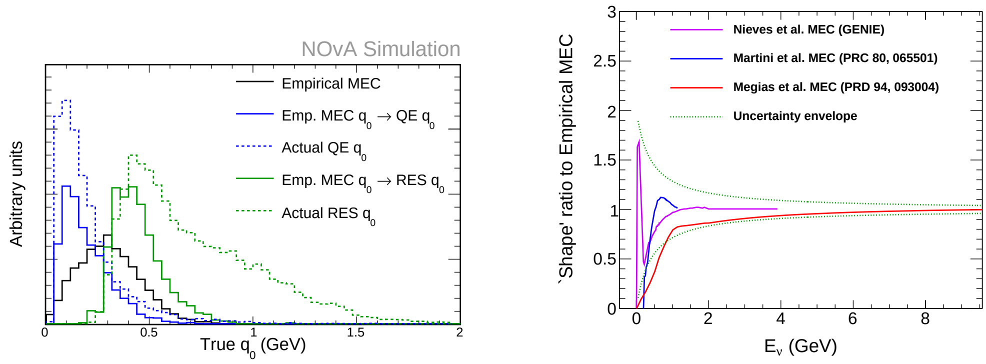
Also critical to any tune is the estimation of systematic errors. A generous 50% normalization uncertainty was applied to the 2p2h mode, but no shape uncertainty was taken into account. Also, the so called random phase approximation (RPA) effect, which describes long-range nuclear charge screening, was not applied to the central value of the tune, but an estimate of that effect was applied as an uncertainty (with a 1-σ shift turning the effect on). The other cross-section uncertainties were taken directly from GENIE.

4. Cross-section tuning: Third analysis

The tuning for our upcoming third analysis, due for release in January 2018, is already complete, and will be detailed next. It should be noted that between the second and third analysis our simulation underwent major upgrades, including the addition of Cherenkov light to the light model, which improves the hadronic energy response in significant ways, thus affecting our tune.

The new tune includes the non-resonant single-pion fix mentioned earlier. It also includes the RPA effect as standard. The RPA model used comes from the MINERvA experiment, but modified to the energy and momentum transfer region relevant for NOvA. This RPA effect is applied only to the QE channel, but it does make a large (around 20%) difference to the overall number of QE events, suppressing events more at lower Q^2 values. This model comes with built-in uncertainties that NOvA uses.

The inclusion of the RPA effect is important, because QE and 2p2h overlap in their hadronic energy distribution. Thus, any attempt to tune 2p2h by fitting it to our ND data is affected. After applying RPA, we took a look at fitting the 2p2h in a similar fashion as was done in our second analysis. We continue to use the empirical MEC model, but instead of matching the energy transfer distribution to that of our QE events, we instead matched it to what is predicted by the Valencia 2p2h model, which is now included in the latest versions of GENIE. We found that the result of our fit was roughly consistent with not changing the empirical MEC model shape at all, but instead just scaling up the normalization by 20%. While this surprised us, we decided to take this central value tune and instead dedicate our efforts to developing robust 2p2h systematics to accompany it. Thus our final central value tune for our third analysis is to apply the following tweaks on top of the standard GENIE output: RPA for QE events, the non-resonant single-pion fix, and empirical MEC included and scaled up by 20% but with the shape unchanged.



(a) Energy transfer distributions

(b) Energy-dependent 2p2h normalization uncertainty

Figure 4: 2p2h systematics

The new 2p2h systematics cover not just normalization, but also shape, an important improvement. Three systematics are included. The most major involves the energy transfer function. The default energy transfer distribution predicted by the empirical MEC model puts 2p2h events between QE and RES events. It is thought that QE and RES should bound the 2p2h region; no theory predicts that 2p2h would have an energy transfer distribution smaller than QE or larger than RES. Thus as a +/-1σ uncertainty, the energy transfer distribution is altered to match that of QE or RES events (shown in Fig. 4(a)). This doesn't change the 2p2h normalization at all, but changes the shape significantly. It should be noted that the conversion from empirical MEC energy transfer to

QE or RES isn't perfect; notable for RES there exists events at high energy transfer that are not properly duplicated when converting the empirical MEC energy transfer distribution as there are no empirical MEC events there to begin with that we can increase the weight of.

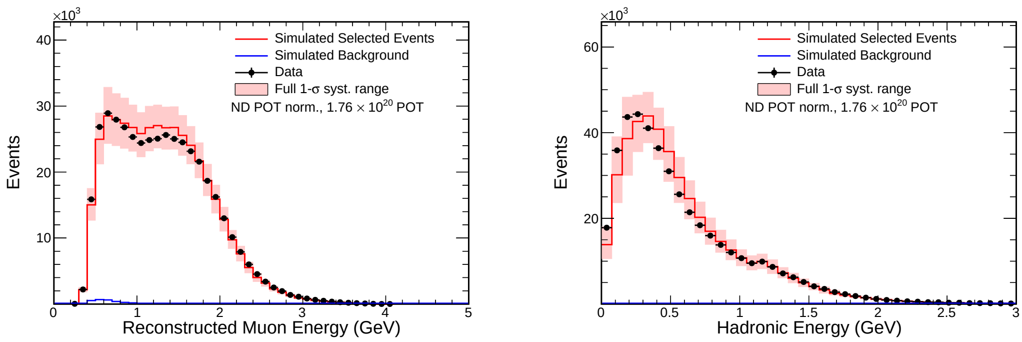
The second 2p2h systematic is a normalization systematic. Different models predict quite different energy-dependent 2p2h cross sections with different shapes. As an attempt to encompass all these possibilities, some popular theories were normalized to each other and over-plotted, and an envelope was found that contained all the models within them. This envelope forms an energy-dependent normalization uncertainty, shown in Fig. 4(b).

The last 2p2h systematic uncertainty we included is the uncertainty on the bound nucleons the neutrino interacts with. While the neutrino interacts with a neutron, that neutron could be bound to either a proton or neutron, and how often it is which isn't certain. The empirical MEC model predicts that 80% of 2p2h events are np bound pairs. We adopted a +/- 10% uncertainty on that prediction as a +/- 1-σ systematic.

One other new addition to the third analysis cross-section systematics is to DIS. In GENIE, DIS events with W $>$ 1.7 GeV use the Rein-Seghal model, where 1.7 GeV is the extreme low end of the region where the model is valid. For DIS events with a W $<$ 1.7 GeV the model is modified with a fit to extra data, which improves agreement. Thus, the events with W just above 1.7 GeV (to 2 or 3 GeV) are somewhat dubious, as they lie at the extreme edge of the model, in a region labeled 'shallow DIS' or 'transition DIS' and known to need further work (for further discussion of this region see the discussion in [6]). NOvA found a disagreement with data in this specific region, and we further found that the standard GENIE systematics in this region were lacking or non-existent. Thus we have added a 50% normalization uncertainty to all these events, which covers the size of the discrepancy with our data.

So our final list of custom systematics we use on top of those provided by GENIE includes: three 2p2h systematics (energy transfer shape, energy-dependent normalization, np/nn fraction), RPA systematics, and new DIS systematics that replace GENIE's for DIS events W $>$ 1.7 GeV.

The result of the tune, showing data vs simulation with a band representing the effects of all NOvA systematics, is shown in Fig 5.

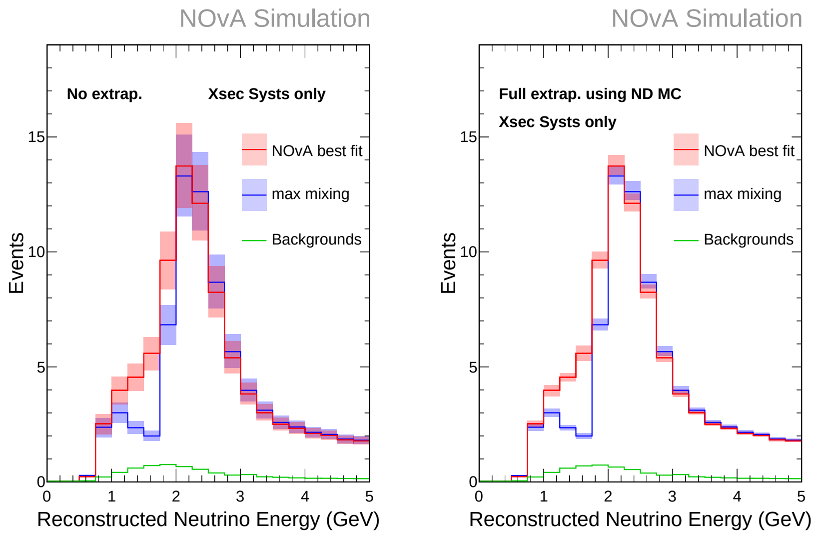


(a) Muon energy (b) Hadronic energy

Figure 5: Final third analysis tune, ND disappearance analysis

5. Size of cross-section systematics in second analyses

One good example of how cross-sections are constrained lie in our NOvA second analysis results. Without detailing the analyses, it can be simply noted that by performing the previously explained extrapolation procedure, the effect of many cross-section systematics are greatly reduced (see Fig. 6). Because of this, the size of these systematics in our final analyses are much smaller than they would otherwise be, and are secondary to our detector effects systematics. As we improve our understanding of our detector effects and collect more statistics, having a better understanding of cross-section effects like 2p2h will become increasingly necessary. Much improvement is also needed to hit DUNE's targeted cross-section uncertainty goals, which will be critical to the success of that experiment. We hope that further measurements from both NOvA and many other experiments like MINERvA and T2K will help shed light on this critical matter in the coming years.



(a) No extrapolation (b) With extrapolation

Figure 6: ND disappearance analysis cross-section systematics

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